TITLE: The Incorporation of Heating Effects in Atmospheric Pressure Gas
Discharge

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The incorporation of heating effects in atmospheric pressure gas discharges

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Abstract

The latest extension of the FE-FCT algorithm used for the solution of gas discharge problems is presented in this paper. The solution of Navier Stoke's equations is coupled to the continuity and Poisson's equations to account for the heating effects of the neutral gas species in near atmospheric pressure gas discharges. Adaptive meshing techniques that adjust the mesh in time are also incorporated, so that the highly transient phenomena involved can be captured. Results are presented for the development of avalanches and streamers in a 1 mm uniform field gap in air at atmospheric pressure, in order to validate the new algorithm. The assumption adopted by many authors to date, namely, that there is no significant heating involved early in the development of such a discharge is investigated.

1. Introduction

The detailed analysis of the spark discharge is important in the design of lasers, exhaust filters and for the protection of microwave systems. Experiments have shown that the spark discharge development after the avalanche and the primary streamer is highly dictated by the heating effects of the neutral gas.

2. Theory

In order to incorporate heating effects in near atmospheric pressure gas discharges, as manifested by the heating of the neutral gas species, the Navier Stoke's equations (conservation of mass, momentum and energy for the neutral gas) need to be coupled to the continuity equations for charged particles (electrons, positive and negative ions) and Poisson's equation for the electric field. The equations are solved in two-dimensional cylindrical axisymmetric coordinates. A Finite Element Flux Corrected Transport method (FE-FCT) has been developed and used for the transport equations [1]. The primary purpose of this work is to validate the new part of the algorithm, i.e. that of the Navier Stoke's in the presence of the continuity equations and Poisson's equations, following the validation of the Navier Stoke's algorithm in [2]. Furthermore, this is the natural progression of previous work by the authors, as they have already simulated the same configuration assuming no heating effects. In this way, the assumption for no heating effects and the validation of the coupling of the Navier Stokes with the Poisson and the continuity equations is achieved. As expected, it has been proven that there is no considerable heating during the avalanche and primary streamer stage and that heating does not significantly affect their development.

3. Adaptive Meshing

The complexity of the new model (coupling of the above three sets of equations) and the computational demand makes the solution of such problems using conventional software very difficult, therefore the authors have developed their own algorithm in C++. An adaptive mesh generator has also been developed such that computational needs are considerably reduced, making it possible to analyse heating effects not only in short gaps, but also in long gaps. The error indicator used for the refinement of the adaptive meshing is the one used by Lohner [3]. The error estimator in multidimensional form is as follows:

$$E^i = \sqrt{\frac{\sum_{k,l}(\int_\Omega N_k^i N_l^j \, d\Omega . U_j)^2}{\sum_{k,l}(\int_\Omega |N_k^i| [| N_l^j U_j | + \varepsilon(| N_l^j || U_j |)]d\Omega)^2}}$$

where E^i is the error indicator value at node i, N_k^i is the shape function of node i in element k, N_l^j is the shape function of node j in element l and U_j is the value of the variable chosen to be used as error indicator at node j and ε is a factor varying from 0 to 1. The value of ε is chosen depending on the algorithm used to solve the partial differential equation, since the term following ε is added as noise filter, so that any loss of monotonicity such as wiggles or ripples are not refined. The authors have used three different variables for error indication, which are the electron density, the positive ion density and the modulus of the electric field.

The advantages of the above error indicator are that it is fast to calculate, it is dimensionless, it varies from 0 to 1 such that prefixed tolerances and many variables as error indicators can be used and that it is reliable for steady state and highly transient applications, as in the case of the development of the spark discharge.

4. Results

In the configuration used to test the heating effects, a voltage of 5600 V is applied between two parallel plates of distance 1 mm apart in ambient air. As an initial condition, a single electron is released at a distance of 1×10^{-4} m from the cathode.

Figure 1 shows the electron density two-dimensional plot as the streamer propagates towards the cathode. Densities of the order of 10^{20} particles/m^3 are in agreement with primary streamer propagation theory.
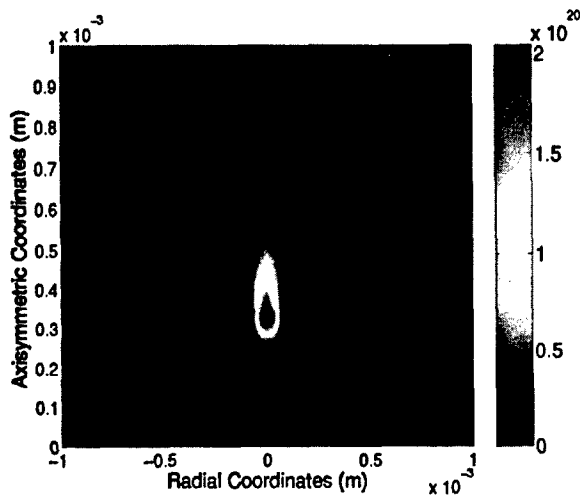

Figure 1: Two-dimensional axisymmetric plot of the electron density of the primary streamer at time t = 4.61 ns.

Figure 2 is a temperature distribution plot during the propagation of the primary streamer towards the cathode. It can be seen that a temperature rise of a few degrees occurs. To test the ability of the heating effects in changing the propagation of the avalanche and the primary streamer, early in its development, it was assumed that all the energy from the electrons, positive and negative ions is transferred to the neutral particles as Joule heating, when charged particles collide with the neutral particles. Taking this into consideration, it is evident that heating does not affect the propagation of the avalanche and primary streamer.

5. Conclusions

As expected, no significant heating arose during the avalanche and streamer propagation that could affect the discharge, and hence the long-held assumption of no heating is justified.

It is now possible to analyse the heating effects of neutral gas species in atmospheric or near atmospheric pressure gas discharges. Heating effects can also be simulated in long gaps, due to the adaptive mesh generator developed. With the densities of the charged particles and the electric field increasing at later stages of the discharge, the heating effects will no longer be negligible, but will dictate the development and behaviour of the spark.
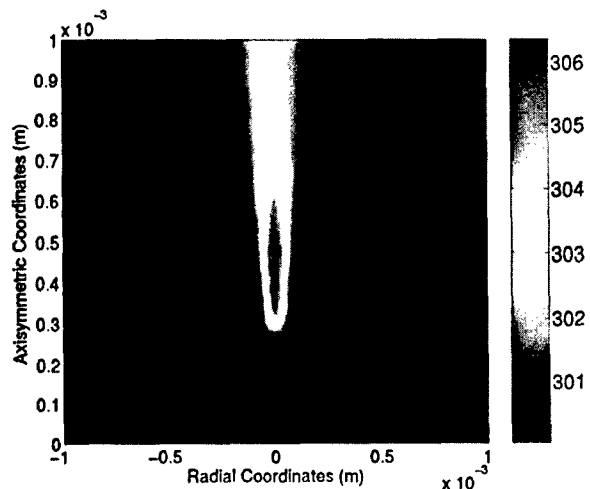

Figure 2: Two-dimensional plot of the temperature during the propagation of the streamer at time t = 4.61 ns.

6. References

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